(54) Title: METHOD OF DETERMINING THE ELECTRICAL PROPERTIES OF THE EARTH BY PROCESSING ELECTROMAGNETIC SIGNALS PROPAGATED THROUGH THE EARTH FROM A CAPACITOR

(57) Abstract

A method of processing electromagnetic signals which are injected into the earth from a capacitor and subsequently detected after reflection from subsurface layers. An initial propagation model (450) which specifies the electrical properties of a particular layer or set of layers is constructed and applied to a model input pulse (460) to produce a predicted return pulse which results from the reflection and/or transmission of the input pulse at the boundaries of the layer(s). The predicted return pulse is then compared to actual return pulse data (470) which is selected so as to roughly correspond to a return pulse produced at the location of the modeled layer(s). The result of the comparison forms the basis for adaptively varying the parameters of the propagation model (480) in a manner which is intended to increase the correlation between the predicted return pulse and actual data.

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Method of Determining the Electrical Properties of the Earth by Processing Electromagnetic Signals Propagated Through the Earth From a Capacitor

This is a continuation-in-part application of
U.S. Patent Application Serial No. 07/713,955, filed
June 11, 1991.

TECHNICAL FIELD

The present invention is generally directed to a
method of determining the electrical properties of
the earth as a function of depth and the frequency of
a signal transmitted into the earth, and more
specifically, to a method of processing
electromagnetic signals which have propagated through
the earth from a capacitor in order to determine such
quantities, and thereby to infer the type of geologic
formations beneath the earth's surface.

BACKGROUND OF THE INVENTION

Throughout the specification, the expressions
"earth" and "earth formation" are used in a broad
sense to denote any nonhomogeneous, dispersive medium
having complex permittivity. Important examples of
such media include subterranean formations such as
soil, hardpan, and bedrock, and bodies of water (such
as the ocean) above such subterranean formations.

Information regarding the electrical properties
(e.g., resistivity, conductivity, relative
permittivity) of a region of the earth can be used
during geophysical exploration in order to assist
with identifying the subterranean formations which
may be encountered. Because of the correlation
between different types of formations and their
electrical properties, an appropriate sampling of
data obtained from a region can be used to identify

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faults, mineral deposits, and the geoelectric
structure of the rock bedding beneath the surface.
One means of determining these electrical properties
is by transmitting an electromagnetic signal downward
5   into the earth and then processing the return signal
which is received after reflection from one or more
layers within the earth, where each layer is
associated with a set of electrical properties.

A "Method and Apparatus for Transmitting
10   Electromagnetic Signals into the Earth from a
Capacitor" is described in allowed U.S. Patent
Application Serial No. 07/713,955, filed June 11,
1991, which is the parent application of the present
continuation-in-part application, and which is hereby
15   incorporated by reference. The parent application
teaches the use of a capacitor to transmit a pulse of
electromagnetic radiation having a broad frequency
band downward into the earth. The inhomogeneous,
dispersive nature of the earth causes the pulse to be
20   partially transmitted and reflected at different
depths or layers. This results in a return signal
being propagated back upward which can be detected by
a similar capacitor.

The processing of the return signal permits the
25   electrical characteristics (such as the relative
dielectric constant and complex resistivity) of the
earth as a function of depth and the frequency
components of the transmitted pulse to be determined.
These characteristics can then be correlated to
30   specific types of subsurface formations in order to
image the subsurface region. Information about the
subsurface formations may then be used to assist with
geophysical exploration.

Of background relevance to the present invention
35   are mentioned methods for modeling the propagation of
radio waves in the ionosphere to determine the values

of the complex indices of refraction for multiple, stratified layers in the propagation medium. For example, the article by J. Ralph Johler (the inventor of the invention described in the present application) entitled "Radio wave reflections at a continuously stratified plasma with collisions proportional to energy and arbitrary magnetic induction", contained in the Proceedings of the International Conference on The Ionosphere held at Imperial College London July 1962, pp. 436-445, published by The Institute of Physics and the Physical Society, and the articles by J. Ralph Johler and John D. Harper, Jr. entitled "Reflection and Transmission of Radio Waves at a Continuously Stratified Plasma With Arbitrary Magnetic Induction", Journal of Research of the National Bureau of Standards, Vol. 66, No. 1, January-February 1962, pp. 81-99, and "On the Effect of Solar Disturbances on the Low-Frequency Ionosphere Reflection Process", contained in The Effect of Disturbances of Solar Origin on Communications, pp. 303-334, G. J. Gassmann editor, published by Pergamon Press, 1963, which are hereby incorporated by reference, discuss a model of the ionosphere which consists of a series of stacked layers of plasma, with each layer being characterized by a complex index of refraction. The propagation of a plane wave through this medium can be modeled according to the methods described in these references and the predicted electron density and collision frequency profiles can be compared to actual measurements as a means of validating the model.

However, the prior art does not teach or suggest how to model the propagation of an electromagnetic signal through the earth to determine electrical properties of interest to geophysical exploration,

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and does not teach or suggest how to determine such
properties in an efficient, iterative manner.

SUMMARY OF THE INVENTION

The present invention is directed to a method of
processing electromagnetic signals which have
propagated through a layered subterranean formation
after having been injected into the earth from a
capacitor, in order to determine physical and
electrical properties of the subterranean formation.

The method is an iterative process and is based
on modeling the earth as a series of vertically
stacked horizontal layers, each characterized by its
physical properties of depth beneath the surface and
thickness, and its electrical properties of complex
resistivity (or conductivity) and relative dielectric
constant. An initial propagation model which
specifies the physical and electrical properties of a
particular layer or set of layers is constructed.
The propagation model is applied to a model input
signal to produce a predicted return signal which
results from the reflection and/or transmission of
the input signal at the boundaries of the layer(s),
and whose form is determined by the impact of the
electrical characteristics of the modeled layer(s) on
the input signal. The predicted return signal is
then compared to (correlated with) actual observed
return signal data which is selected so as to roughly
correspond to a return signal produced at the
location of the modeled layer(s). The result of the
comparison forms the basis for adaptively varying the
parameters of the propagation model in a manner which
is intended to increase the correlation between the
predicted return signal and the actual data.

When a desired degree of correlation is
achieved, the parameters of the propagation model are

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interpreted as representing the actual electrical and physical characteristics as a function of depth and frequency of a geoelectric column at the location of the injected signal, i.e., the resistivity and dielectric properties of a sequence of vertical layers whose boundaries are determined by the variations in the electrical properties of the layers. In principle, a geoelectric column represents a local vertical variation of these properties at a particular location. Repetition of the method for different layers or additional locations thus permits the electrical characteristics of the earth beneath a specified region to be determined. Knowledge of these characteristics can then be used to infer the type of geologic formation responsible for transforming the input signal into the received data.

BRIEF DESCRIPTION OF THE DRAWINGS

    Figures 1a, 1b, 1c, and 1d show several embodiments of capacitor terminal pairs suitable for use in transmitting or receiving signals which are to be processed according to the method of the present invention.

    Figure 2 is a perspective view of an apparatus for the generation and application of signals to the terminals of an earth capacitor, and for receiving return signals which have propagated through the earth.

    Figure 3 is a block diagram of the processing scheme of the present invention which is used to model the physical and electrical properties of the earth.

    Figures 4a and 4b depict respectively, a section of the earth illustrating several vertically stacked horizontal layers whose physical and electrical

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properties can be determined by the method of the
present invention, and the coordinate system used in
the description of the method of the present
invention.

5 DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

Figures 1a through 1d show several embodiments
of capacitor terminal pairs suitable for use in
transmitting or receiving signals which are to be
processed according to the method of the present
10 invention. Each capacitor terminal pair depicted in
Figure 1 includes a set of terminals which permit an
electrical pulse of energy to be injected into the
earth or a return signal corresponding to that pulse
to be received (after having propagated through the
15 earth).

The simplest set of terminals, shown in Figure
1a, includes transmitted pulse input terminals **311**
and **312** received pulse terminals **321** and **322**.
Terminals **311**, **312**, **321**, and **322** comprise metallic
20 pins or electrodes driven into the earth, either
partly or completely beneath the earth's surface **130**.
If a high voltage electrical pulse is applied to
transmitting terminals **311** and **312**, a return pulse
can be detected at receiving terminals **321** and **322**
25 after having propagated through the earth. The
nature of the received signal will in large measure
be dependent upon the electrical characteristics of
the earth **130a**.

A more convenient and effective apparatus for
30 injecting pulse energy into the earth **130a** is
depicted in Figure 1b, which shows a transmitting
device and a receiving device which each include a
metal plate, **210** or **220**, with greatest dimension, L
and a single metallic pin or electrode. The input
35 terminals consist of a terminal **211** or **221** on each

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plate **210** or **220**, and a terminal on the pin that has been driven into the earth, **212** or **222**. Here an electrical pulse applied to the transmitter terminals, **211** and **212** will produce an earth response at the receiver terminals, **221** and **222**. This earth response can be observed and recorded.

Earth pulse excitation terminals which are balanced with respect to the ground in such a manner as to be more convenient and more efficient than those shown in Figures 1a and 1b, are shown in Figure 1c. Here metallic plates **10**, **10a**, **10b**, and **10c** are shown with terminals **11**, **11a**, **11b**, and **11c** respectively, and terminals **12**, **12a**, **12b**, and **12c** respectively. The greatest dimension of each plate pair is designated by L, and the flare angle of plate **10** is designated by F. A cross section representative of each of plates **10**, **10a**, **10b**, and **10c** is shown in Figure 1d. Here plate **10** for example, is shown firmly placed on the earth, **130a** at the earth's surface **130**. Terminals **11** and **12**, which may be for either input or output together with the greatest dimension, L, are shown. Such a configuration is termed an earth capacitor if the critical dimension L and the area of the plates are selected so that the input terminals exhibit resistive and capacitive impedance components within the desired frequency regime described in the parent application.

Figure 2 depicts a perspective view of an application of the earth capacitor apparatus of Figure 1 which is described more fully in the above-referenced parent application. Metallic plates **10** and **20** of copper or brass shaped as flat circular sections of overall length L and flare angle F are snugly placed on the surface of the earth **130**. Plates **10** and **20** may or may not be coated with one to

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two millimeters of plastic for protection. Typical
values for L and F are 0.5 meters and 90 degrees,
respectively. The apex from which the flare radiates
contains an insulated gap across which two terminals,
5   11 and 12 or 21 and 22, are arranged.

Terminals 11 and 12 or 21 and 22 are balanced
electrically with respect to the earth and this
balance is maintained with the aid of a transmission
line balun (balanced to unbalanced transmission line
10   transformation) 30 or 40. Thus, pulse generator 50,
if capacitor apparatus 10 and 30 is to be used as a
transmitter, or amplifier 90, if capacitor apparatus
20 and 40 is to be used as a receiver are unbalanced
to the ground and a suitable unbalanced-to-balanced
15   transformation must be made to the apex points, 11
and 12 or 21 and 22 with balun 30 or 40. This
describes the elements of the capacitor apparatus:
two metallic plates and a "dielectric" or earth in
contact with and common to both sets of plates.

20   Since the permittivity and/or the conductivity
of the material with which the plates are in contact
may be, and indeed usually is a complex quantity, and
more importantly, since radiation is lost into the
earth, the configuration presents both capacitive and
25   resistive components to the input impedance at the
apex points where the transmission line balun is
connected. The earth 130 has thus been placed in an
electrical circuit with pulse generator 50, which
typically operates at an impedance level of 50 ohms
30   with respect to short cable connection 63. Elements
10, 30, 50, and 63 are capable of coupling extremely
high voltage pulses into the earth although low
voltage pulses, of the order of 300 to 2500 volts,
have been found to be generally useful in earth
35   subsurface applications.

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The scheme depicted in Figure 2 can be used for probing the electrical properties of subterranean earth formations. This is best accomplished by injecting high energy pulses into the earth and detecting the resulting return pulses that have propagated through the earth. The pulses are timed by oscillator or timer 60 which is supplied with power through cable 70 via oscilloscope, digitizer and amplifier apparatus 90. A synchronizing pulse is transmitted to pulse generator 50 over cable 62 while power cable 61 powers the pulser. DC power supply 110 provides power from a remote location with respect to capacitor apparatus 10 or 20.

Switch 111 is used to shut off the pulser while at the same time maintaining the synchronizing signal for purposes of noise sampling of the return signal environment. The synchronizing pulse or signal is supplied to oscilloscope and digitizing apparatus 90 via cable 70. Thus cable 70 carries DC power and synchronizing pulse together with on/off information for the pulser. The pulse signal is injected into the earth 130 via plates 10 in time synchronization from pulser 50. The separation between transmitting apparatus 10, 30, and 50, and the receiving apparatus 20, 40, and 90 may vary from about 6 to 100 meters, although a separation of 6 meters has been used most extensively by the inventor up to this date. The preferred design and method of operation of the Fig. 2 apparatus, to obtain return pulses that have propagated from a desired subterranean depth, are described in the parent application.

The pulse wavelets returning from the depths of the ground are collected in various time windows opened in time relative to the synchronization pulse. Returning pulses are digitized by digitizing apparatus 90 and processed through computer and

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recording apparatus **100**. The data in digital form is then stored on floppy disks (or other suitable medium) for permanent storage and future processing. Most of the equipment can be conveniently located in a motor vehicle and AC power can be supplied by a small portable alternator **120**.

In accordance with the present invention, the processing of the data stored on the floppy disks is described with reference to Figure 3, which is a block diagram of the processing scheme of the present invention and which is used to model the physical and electrical properties of the earth. The unit of time, t, over the observed waveform is fundamentally the second. However, very short times of the order of several thousand nanoseconds (ns, where 1 ns equals 1×10^{-9} seconds) are relevant when discussing the time scale of the method of the present invention. This time scale is largely a consequence of the constant, c = .299792458 meters per nanosecond, the so called "speed of light".

The observed time domain data is usually stored in overlapping time windows such as 0 - 10000 ns, 2000 - 12000 ns, 5000 - 15000 ns, 10000 - 20000 ns, etc. It has been found that each of these time regimes correspond to a depth regime (in feet for example) relative to sea level. The relationship, however is not linear because the electrical properties of the ground vary with both depth and frequency, and in particular with the type of rock formation or "stratum" encountered by the electrical pulse.

With reference to Figure 3, the observed data (for a return pulse) is initially stored in observed data storage **400**. A portion of the stored data which corresponds to a desired time window (and hence an approximately known depth regime) is then selected

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(as indicated by box **410**). This actual received
pulse data will ultimately be compared to the
received pulse predicted by a propagation model so
that, in accordance with the method of the present
5   invention, the electrical properties of the earth
layer which corresponds to the depth regime may be
determined.

The observed time domain data corresponding to
the selected time window is then replicated, i.e.,
10   put into a mathematical form that represents the
actual observed data to a desired degree of accuracy.
This may be accomplished for example, by digitization
and then transformation to the frequency domain by
means of a Fourier transformation (step **414**),
15   followed by further data manipulations such as
filtering or deconvolution which serve to put the
observed data into a useful form. For instance, the
digitized and transformed data may be subjected to a
spectrum normalization filter **420** (similar to a
20   deconvolution operation), which insures that the
various components of the spectrum in the frequency
range corresponding to the selected time window are
given substantially the same weight so that a single
line spectrum does not dominate the window. The data
25   may also be subjected to a filter which limits the
range of frequency components being used in later
steps of the method. After spectrum normalization
(step **420**) and/or any other desired manipulations,
the data is stored (step **430**) and in this form
30   becomes a constant of the process.

The next stages of the method produce simulated
received data which will be compared to the data
stored in a storage device during step **430**. Data
manipulations of the simulated received data are
35   generally performed in the frequency domain where the
data may be subjected to similar filtering and/or

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deconvolution operations as those performed on the
actual observed data after its transformation to the
frequency domain. After the received data has been
produced by the model and undergone any desired
5   manipulations, both the actual data and the simulated
received data are transformed back to the time domain
where they are compared to assess whether further
changes to the model's parameters are required.

        The production of simulated received data
10   begins, if desired, by selection of a model input
signal as shown in box **450**. The input signal may be
represented by a delta function (for an impulse
function), a square wave, or other desired form. It
is also possible to simply let the model run through
15   its iterations without specifying the form of the
input signal. However, for operation on a portable
computer, it is more efficient to begin with a
defined input signal. The frequency domain spectrum
of a model time domain waveform may be obtained by
20   application of a Fourier transform (step **454**). The
spectrum of the input signal may then be restricted
and modified by digital filtering and/or spectrum
normalization as was discussed above with reference
to the manipulation of the observed data (also step
25   **454**). A physical model of the propagation of an
input signal through the earth is then applied to the
frequency domain representation of the input signal,
as indicated by box **460**.

        The propagation model is based upon Maxwell's
30   equations and is introduced to describe the
propagation of the frequency domain representation of
the input signal downward through a layer or
vertically stacked horizontal layers of the earth and
then back upward to the surface by virtue of
35   reflections occurring at the boundary between
different horizontal layers. The model can be made

more accurate by introducing a representation of the
input signal (which may be based on a model of the
source producing the signal) and modeling the
coupling mechanism of the signal into the ground.
The actual received pulse waveforms in the selected
time window, after having been transformed to the
frequency domain, undergoing desired manipulations
and then being stored (step 430), are transformed
back to the time domain and then compared with the
result of transforming to the time domain the result
of applying the propagation model to the frequency
representation of the model input signal, and the
degree of correlation between the two sets of data is
determined (step 470).

Based on the result of the comparison step, the
modeling process is either stopped (box 500), or if
the degree of correlation is not equal to that
desired, a basic parameter adjustment of the model is
performed (box 480). The modified propagation model
is then applied to the model input signal (in a
second iteration of step 460), followed by another
transformation to the time domain and comparison step
(a second iteration of step 470). This cycle is
repeated until the maximum or desired degree of
correlation is achieved. When this has occurred, the
final output is the most recently modified model,
which comprises a geoelectric column for the
particular locality together with the basic
electrical parameters of the iteration. These
parameters are the complex resistivity and dielectric
property of each of the horizontal layers assumed by
the model, together with the thickness of each layer.
The resistivity versus depth and frequency, and the
dielectric property versus depth and frequency of the
earth formation are determined by the corresponding

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parameters used in the propagation model in order to
obtain the desired degree of correlation.

Since the propagation model models the earth as
a sequence of vertically stacked horizontal layers,
each characterized by a set of electrical and
physical parameters, and since the model responds
only to upward and downward traveling waves,
iterations of steps **460**, **470**, and **480** of the Figure 3
method in effect comprise a filter that removes the
non-vertically traveling waves. This is largely
possible since vertically traveling waves are usually
dominant in the selected frequency window. The
iteration loop (including loop portion **490**) may
therefore be referred to as a filter loop.

In understanding the invention, it is helpful to
appreciate that the propagation of electromagnetic
signals in the earth is much more complicated than in
the atmosphere. When an electromagnetic pulse is
coupled to the earth, return pulses from depths
greater than a few hundred feet in the earth seem to
vanish. However, the inventor of the present
invention has recognized that the earth supports
pulse propagation through much longer distances, and
in all types of subterranean formations. Usually,
pulse dispersion occurs with the result that the
frequency window of a return pulse is shifted to a
lower frequency regime relative to the frequency
window of the originally transmitted pulse.
Accordingly, unless observations are made in the
proper frequency window, an observer may incorrectly
conclude that a return pulse has been lost in the
noise.

The inventor has recognized that it is usually
irrelevant to detect and process a return signal in
the same frequency window as that of a transmitted
signal, and in fact in a preferred embodiment, the

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voltage pulse applied to the transmitting capacitor
has frequency components in a broad band from below 1
MHz to above 100 MHz, and the frequency components of
the detected electromagnetic radiation that are
5   processed to image the subsurface have a frequency in
the range from about 500 KHz to 25 MHz.

The iterative cycling which has been described
with reference to Figure 3 is continued until the
correlation between the observed and predicted time
10   domain waveforms corresponding to the particular time
window is maximized or reaches a desired value,
usually of the order of 70% to 95%. For greater
accuracy the stratification, i.e., the number of
layers specified in the model applied in each
15   iteration of step 460 can be increased indefinitely.
This is particularly desirable when sufficient
computing resources are available, as such an
approach allows the propagation medium to be modeled
as a continuum. After performance of step 500 (see
20   Figure 3), exploration of other depth regimes (time
windows) can then be undertaken by again performing
all steps of the method to process another set of
data (selected during another step 410) until a
complete geoelectric column is obtained. A sequence
25   of such geoelectric columns over an area can then be
used to indicate the nature of the subsurface geology
from an electrical point of view, and can be used to
assist in identifying faults, special mineral
deposits, and the geoelectric structure of the rock
30   bedding.

The remaining portions of this specification
will be devoted to providing a more detailed
description of the structure of the propagation model
and the operation of the parameter adjustment loop
35   depicted in Figure 3. The development of the earth
capacitor concept described in this and its parent

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application is based upon extensive observations by the inventor and others over a variety of geographical locations in Wyoming, Colorado, New Mexico and Texas. In these observations it became apparent that the various waveforms observed and recorded via the reception recorder were a consequence of the electrical pulse excitation of the input pulse and the corresponding response of the earth from the various depths, where the response depended on the electrical properties of subterranean geologic formations. It was further observed that the earth response comprised pulse wavelets traveling primarily in the direction perpendicular to the various earth formations or essentially comprised a system of waves, or in the cases of pulses, comprised a system of pulse wavelets traveling upward and downward through the various geologic formations.

The mathematical construction which will be described applies the notion of stratification but is sufficiently simple as to be handled on a modern personal computer (PC), yet sufficiently complex to be capable of yielding a practical level of accuracy when characterizing the geoelectric column at a surface point location in a subsurface survey. It is believed that characterization of geoelectric structure to depths of the order of 20000 feet or greater may be possible using this method of analysis. It should be obvious that the model applied during any repetition of step 460 can be improved in its degree of sophistication and rigor as greater computing power becomes available.

Each frequency domain component of the downward traveling signal resulting from the application of an electrical pulse to the terminals of an earth capacitor, having a particular frequency f (in Hertz), at a distance D (in meters) below the

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horizontal location of the capacitor terminal, can be
described by the mathematical form:

$$E(\omega,D) = |E(\omega,D)| \exp(\omega \text{ß} D/c) \exp(i\omega t - i\omega D/V_c), \text{ where} \quad (1)$$

ß is the attenuation factor, V_c is the phase velocity,

5   f is the frequency in Hertz, and $\omega = 2\pi f$. The phase
velocity V_c is equal to c/α, where α is the real part
of the complex index of refraction.

For the purposes of the present invention, the
fundamental electrical parameters for a vertically

10   stacked horizontal layer of the earth which is
characterized by the index k, are given by:

ϵ_k = the relative dielectric property (permittivity)
of the kth layer;
ρ_k = the resistivity in ohm-meters of the kth layer;

15   and
σ_k = the conductivity in mhos per meter of the kth
layer.

With the above definitions, the attenuation factor ß
and the quantity α can be further defined as:

20         $$\text{ß} = A \operatorname{Sin}(\theta) \text{ and}$$
$$\alpha = A \operatorname{Cos}(\theta), \text{ where} \quad (2)$$

$$A = [\epsilon_k^2 + (\sigma_k / (\epsilon_0 \omega))^2]^{1/2} \text{ and} \quad (3)$$
$$\theta = .5 * \operatorname{Tan}^{-1}(-\sigma_k / \epsilon_0 \epsilon_k \omega). \quad (4)$$

Here $\epsilon_0 = 1 / (c^2 \mu_0)$ where c equals the speed of light

25   in vacuum and μ_0 is the permeability in vacuum and has
a value of $4\pi \times 10^{-7}$ henry per meter. The complex index
of refraction for the kth layer is given by n_k, where
$n_k = \alpha_k + i\text{ß}_k$. By way of example, for air $n_k =$
1.000338, while for a vacuum $n_k = 1.0$.

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The method of the present invention uses a transformation between the time and frequency domains (a Fourier Transform-Integral) which is described by:

$$E(t,D) = (1/2\pi) \bullet$$
$$\int_{-\infty}^{+\infty} \exp(i\omega t)\ E(\omega,D)\ f_r(\omega)\ \int_0^\infty \exp(-i\omega\tau)\ F_s(\tau)\ d\tau\ d\omega, \quad (5)$$

where $E(t,D)$, the time domain representation, is dependent on the inner integral which in turn depends on the form of a pulse F_s which is transformed to the frequency domain, and then multiplied by the transform of the propagation medium and other appropriate quantities. In equation (5), D is the distance into the earth in meters, and the local time t and universal time τ are related by:

$$t = \tau - \alpha_k D/c. \qquad\qquad (6)$$

The quantity F_s can be thought of as the current in the transmitting capacitor dielectric, that is the current about the capacitor plates in the topmost layer of the non-homogeneous earth as a function of time. The quantity f_r represents the frequency dependence of the earth capacitor when acting as a transmission device into the earth or as a receiving device for pulse energy emerging from the earth. The nature of F_s and f_r have been determined experimentally and can be inferred from application of the method of the present invention to real earth pulse response data. Possible representations of F_s and f_r will be presented later in this application.

Figure 4a depicts a section of the earth and illustrates several vertically stacked horizontal layers whose physical and electrical properties (that is a geoelectric column) can be determined by the method of the present invention. Figure 4b depicts

the coordinate system shown in figure 4a in its usual
upright orientation, for purposes of clarity. A
system of transverse waves is to be constructed for
this arbitrary set of horizons. The system can be
constructed such that the waves are traveling in the
vertical z-direction or tilted in an arbitrary
direction such that the coordinate systems xyz and
x'y'z' do not coincide. In figures 4a and 4b, ϕ_i
represents the deviation of the waves from the
vertical z-direction, and ϕ_a represents the azimuth
angle.

Using equation (1) as a solution of Maxwell's
equations for one frequency component of a wave
propagating through the earth, a boundary condition
for the continuity of the tangential electric field
at the boundaries of each layer z_1, z_2, ... z_k is
imposed. Using methods known in the art, this leads
to the development of a system of equations which can
be solved to yield the electrical parameters of the
layers.

If equation (1) is rewritten in the form:

$$E(\omega,D) = |E(\omega,D)|\exp(i\omega t - i\omega^n D/c), \text{ where } n = \alpha + i\beta,$$

then $^n D$ can be written:

$$^n D = x \sin\phi_i \sin\phi_a + y \sin\phi_i \cos\phi_a + z \varsigma. \tag{7}$$

This form is particularly useful because, as will be
seen, the quantity ς is related to the electrical
parameters of the layers. The equations which result
from imposing the boundary condition for the
continuity of the field across each boundary of the
layers can be written in a compact form by defining
the quantity $Q = E_x/E_y$. With this definition, the
following set of equations is formed for the E_x field
($\phi_a = \pi/2$), for the example of three layers:

$$E_{y'i} \cos \phi_i - E_{y'r} \cos \phi_i = Q_i^{(1)} E_{yi}^{(1)} + Q_r^{(1)} E_{yr}^{(1)}; \qquad (8)$$

$$Q_i^{(1)} E_{yi}^{(1)} \exp[-i\omega z_1 \varsigma_i^{(1)}/c] + Q_r^{(1)} E_{yr}^{(1)} \exp[-i\omega z_1 \varsigma_r^{(1)}/c] = Q_i^{(2)} E_{yi}^{(2)} + Q_r^{(2)} E_{yr}^{(2)}; \text{ and}$$

$$Q_i^{(2)} E_{yi}^{(2)} \exp[-i\omega z_2 \varsigma_i^{(2)}/c] + Q_r^{(2)} E_{yr}^{(2)} \exp[-i\omega z_2 \varsigma_r^{(2)}/c] = Q_i^{(3)} E_{yi}^{(3)}.$$

In the above equations (8), the subscripts y' or y refer to the appropriate coordinate system, the subscripts i or r refer to either the downgoing wave or the upgoing (reflected) wave, respectively, and the numerical indices refer to the noted layers.

Equations similar to equations (8) above are produced for each layer in the model. The last (deepest) layer is usually assumed to be infinite so that no upgoing waves are present. A similar set of boundary conditions is also produced for the E_y component of the electric field, and for the H_x, and H_y components of the magnetic field. These equations are then reduced to the following system of equations:

$$
\begin{array}{cccccccc}
a_{11} & a_{12} & a_{13} & & & & & \\
a_{21} & a_{22} & a_{23} & & & & & \\
 & a_{32} & a_{33} & a_{34} & a_{35} & & & \\
 & a_{42} & a_{43} & a_{44} & a_{45} & & & \\
 & & & a_{54} & a_{55} & a_{56} & a_{57} & \\
 & & & a_{64} & a_{65} & a_{66} & a_{67} & \\
 & & & & & a_{76} & a_{77} & a_{78} & a_{79} \\
 & & & & & a_{86} & a_{87} & a_{88} & a_{89} \\
 & & & & & \cdot & \cdot & \cdot & \cdot & \cdot \\
 & & & & & \cdot & \cdot & \cdot & \cdot & \cdot
\end{array}
\begin{array}{c}
R_m \\
U_{i1} \\
U_{r1} \\
U_{i2} \\
U_{r2} \\
U_{i3} \\
U_{r3} \\
U_{i4}
\end{array}
\begin{array}{c}
a_{10} \\
a_{20} \\
\\
= \\
\\
\\
\\
\end{array}
$$

where U_{in} is proportional to the downgoing wave in the nth layer, U_{rn} is proportional to the upgoing wave in the nth layer, and R_m is the total reflection back to the receiving capacitors (the net reflection coefficient as measured at the surface). The system

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of equations shown in (9) is representative of a
model having 4 layers. As mentioned, the last layer
is assumed to be infinite and having no upgoing wave.

The terms in the above system of equations are:

5

$a_{10}=1$	$a_{32}=\exp(-ik_0z_1\zeta_{i1})$	$a_{54}=\exp(-ik_0z_2\zeta_{i2})$
$a_{20}=-\cos(\phi_i)$	$a_{33}=\exp(-ik_0z_1\zeta_{r1})$	$a_{55}=\exp(-ik_0z_2\zeta_{r2})$
$a_{11}=-1$	$a_{34}=-1$	$a_{56}=-1$
$a_{12}=-1$	$a_{35}=-1$	$a_{57}=-1$
$a_{13}=-1$	$a_{42}=\zeta_{i1}\exp(-ik_0z_1\zeta_{i1})$	$a_{64}=\zeta_{i2}\exp(-ik_0z_2\zeta_{i2})$
$a_{21}=-\cos(\phi_i)$	$a_{43}=\zeta_{r1}\exp(-ik_0z_1\zeta_{r1})$	$a_{65}=\zeta_{r2}\exp(-ik_0z_2\zeta_{r2})$
$a_{22}=\zeta_{i1}$	$a_{44}=\zeta_{i2}$	$a_{66}=\zeta_{i3}$
$a_{23}=\zeta_{r1}$	$a_{45}=\zeta_{r2}$	$a_{67}=\zeta_{r3}$,

10

where ζ is as defined in equation (7) and can be
expressed as $n^2 = \zeta^2 + \sin^2(\phi_i)$ with $\phi_a = \pi/2$.

15

The wave system traveling in the downward,
z-direction in Figure 4a (the E_i waves) gives rise to
upgoing waves in the negative z-direction (the E_r
waves) as a consequence of the change in electrical
characteristics at the boundaries of layers z1, z2.
z3 ... such that E_i, the incident wave into the earth
at the top layer, and E_r, the net upgoing wave at the
top layer are related by:

20

$$E_r = E_i R_m \qquad (10)$$

where R_m is as defined above.

25

The solution for the total reflected or E_r wave
depends on R_m, which can be written:

$$R_m = (R_{m,0} - T_1)/(1 - R_{m,0}T_1) \qquad (11)$$

where,

$$R_{m,0} = [\cos(\phi_i) - \zeta_i]/[\cos(\phi_i) + \zeta_i)] \qquad (12)$$

30

$$T_1 = \exp(-2k_0z_1\zeta_{i1})(1 - R_1T_2)/(T_2 - R_1) \qquad (13)$$

$$R_1 = (1 - \zeta_{i2}/\zeta_{i1})/(1 + \zeta_{i2}/\zeta_{i1}) \qquad (14)$$

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$$T_2 = \exp(-2k_0 z_2 \zeta_{i2})(1 - R_2 T_3)/(T_3 - R_2) \tag{15}$$

$$R_2 = (1 - \zeta_{i3}/\zeta_{i2})/(1 + \zeta_{i3}/\zeta_{i2}) \tag{16}$$

. . .

. . .

$$R_{N-1} = (1 - \zeta_N/\zeta_{N-1})/(1 + \zeta_N/\zeta_{N-1}) \tag{17}$$

$$T_N = 0$$

$$T_{N-1} = \exp(-2ik_0 z_{N-1} \zeta_{i(N-1)})/R_{N-1} \tag{18}$$

The number N is the number of horizons in the model
of that region of the earth. The above equations
thus provide a recursive method of determining the
quantities R_N and T_N.

The transmission into the earth is determined by
the complex quantities U_{in} and U_{rn}, which are
transmission coefficients for downgoing (i) or
upgoing (r) waves into or from the layer specified by
the index n. These waves can be calculated from the
matrix equation (9), which, after considerable
manipulation can be reduced to the following:

$$R_m = (R_0 - T_1)/(1 - R_0 T_1) \tag{19}$$

$$U_{i1} = U_0/(1 - R_0 T_1) \tag{20}$$

$$U_{r1} = U_0 T_1/(1 - R_0 T_1) \tag{21}$$

$$U_{i2} = U_0 U_{01} R_1/[(1 - R_0 T_1)(R_1 - T_2)] \tag{22}$$

$$U_{r2} = U_0 U_{01} R_1 T_2/[(1 - R_0 T_1)(R_1 - T_2)] \tag{23}$$

$$U_{i3} = U_0 U_{01} U_{02} R_1 R_2/[(1 - R_0 T_1)(R_1 - T_2)(R_2 - T_3)] \tag{24}$$

$$U_{r3} = U_0 U_{01} U_{02} R_1 R_2 T_3/[(1 - R_0 T_1)(R_1 - T_2)(R_2 - T_3)] \tag{25}$$

. . .

. . .

$$U_{in} = (U_0 U_{01} U_{02} \ldots U_{0(n-1)})(R_1 R_2 \ldots R_{(n-1)})/[(1 - R_0 T_1)$$
$$(R_1 - T_2) \ldots (R_{(n-1)} - T_n)] \tag{26}$$

where $T_n = 0$ for n=N, if N horizons exist. Based upon
these definitions:

$$U_0 = -2\cos(\phi_i)/[\cos(\phi_i) - \zeta_{i1}] \tag{27}$$

23

$$U_{01} = 2 \exp(-ik_0 z_i \zeta_{i1}) / (1 - \zeta_{i2}/\zeta_{i1}) \qquad (28)$$

$$U_{02} = 2 \exp(-ik_0 z_2 \zeta_{i2}) / (1 - \zeta_{i3}/\zeta_{i2}) \qquad (29)$$

$$\cdot \quad \cdot \quad \cdot$$

$$\cdot \quad \cdot \quad \cdot$$

5   The above expressions (20 to 29) completely
describe the earth model electric field at any point
below the surface of the earth. The particular
filter of importance to the recovery of the

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geoelectric column requires:

$$\phi_i = 0 \qquad\qquad (30)$$

This value of ϕ_i has the effect of filtering out the non-vertically traveling waves (see figure 4a) by making the vertical direction perpendicular to the wavefronts.

It is now desired to solve equation (1) for the frequency domain model signal for the ratio, W_1, of the amplitudes of the upgoing (r) to the downgoing (i) waves at the earth's surface (i.e., R_m):

$$E_r(\omega)/E_i(\omega) = W_1 \qquad\qquad (31)$$

Now define:

$$A_n = \exp(2ik_0 z_n \zeta_n)/R_n \qquad\qquad (32)$$
$$E_n = \exp(2ik_0 z_n \zeta_n) \qquad\qquad (33)$$
$$R_n = (1 - \zeta_{(n+1)}/\zeta_n)/(1 + \zeta_{(n+1)}/\zeta_n) \qquad\qquad (34)$$

where R_n is the reflection coefficient at the top of the nth layer, and then proceed to calculate the ratios W_N, where W_N is the ratio of the upgoing to downgoing waves at the Nth layer, as follows:

$$W_{(N-1)} = \frac{1 - A_{(n-1)}R_{(N-2)}}{A_{(N-1)} - R_{(N-2)}} \bullet E_{(N-2)} \qquad\qquad (35)$$

$$W_{(N-2)} = \frac{1 - W_{(N-1)}R_{(N-3)}}{W_{(N-1)} - R_{(N-3)}} \bullet E_{(N-3)} \qquad\qquad (36)$$

$$W_{(N-3)} = \frac{1 - W_{(N-2)}R_{(N-4)}}{W_{(N-2)} - R_{(N-4)}} \bullet E_{(N-4)} \qquad\qquad (37)$$

. . .

25

$$W_n = \frac{1-W_{(n+1)}R_{(n+3)}}{W_{(n+1)} - R_{(n+3)}} \bullet E_{(n+3)} \tag{38}$$

$$\bullet \quad \bullet \quad \bullet$$

until n = 1.

The spectral relation between time, t and depth D can be established as follows:

$$\Psi_n^{ns} = \frac{2(10)^9}{c} \Sigma_{k=1}^n z_k \varsigma_k \tag{39}$$

$$\frac{\delta D_k}{\delta \Psi_k} = \frac{D_k - D_{(k-1)}}{\Psi_k - \Psi_{(k-1)}} \tag{40}$$

$$D_p^{ft} = [\Sigma_{k=1}^n 2z_k + (t_p - \Psi_p) \bullet \frac{\delta D_n}{\delta \Psi_n}] \bullet 1.641 \tag{41}$$

where Ψ_n^{ns} is the propagation time in nanoseconds for a wave traveling into layer n, and D_p^{ft} is the depth in feet calculated at the time t_p(ns). This relationship allows the depth at which a layer is located to be correlated with a time or time window in which a return pulse is detected. The depth estimated by this method will vary somewhat with the frequency used. The actual depth of a layer is an output of the model after its final iteration.

The method of the present invention is performed on waves having a set of frequency components in the frequency domain which correspond to the selected time window in the time domain. The relationship between time and depth is related to the frequencies in the frequency window and can be estimated from equation (41). In practical terms, an initial time window is selected and the depth regime corresponding to that window is determined, typically at a frequency of 1 MHz. This correspondence can then be checked at another frequency, for example 10 MHz. Further, the initial depth regime can be associated

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with a number of layers, each with specified values
for the physical and electrical parameters.

To facilitate calculations, the inner integral
of equation (5) can be written compactly as follows:

5

$$E(\omega) = TE(t) \tag{42}$$

Now let:

$$F(\omega) = Ln[[E(\omega)\exp(i\omega t)]^* [E(\omega)\exp(i\omega t)]] \tag{43}$$

where the first factor in equation (43) is the
complex conjugate of the second factor. Then the

10   outer integral of equation (5) can be regarded as the
inverse of equation (42):

$$E_s(t) = T^{-1}F(\omega). \tag{44}$$

Setting $E_s(t) = 0$ when $t < 0$ gives:

$$E_s(\omega) = TE_s(t), \tag{45}$$

15   whereupon the desired spectrum normalization filter
becomes:

$$W_s(\omega) = 1/\exp[E_s(\omega)]. \tag{46}$$

The normalization filter tends to give more equal
weight to the various discrete spectral components in

20   the selected frequency window. The replication in
the time domain is then as follows:

$$E(t) = T^{-1} E(\omega)W_s(\omega), \tag{47}$$

$$E(\omega) = \int_{-\infty}^{+\infty} u(t) \exp(-i\omega t) E(t) \, dt \tag{48}$$

where $u(t)=0$, $t>T_2$ $t<T_1$; else $u(t)=1$, which defines T.

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Also,

$$E(t) = (1/2\pi) \int_{-\infty}^{+\infty} v(\omega) \exp(i\omega t) E(\omega) W_s(\omega) d\omega, \quad (49)$$

where $v(\omega)=1$, $-F_2>f<-F_1$; $F_1<f<F_2$; else $v(\omega)=0$, which
defines T^{-1}. Thus, ordinary replication of the data
implies $W_s = 1$ while replication using normalized
spectrum filtering, Ws is defined by equation (46).
Furthermore, the time window is defined by T1 and T2
and the frequency window is defined by F_1 and F_2.

The preceding discussion has focused on the
construction of the model input signal indicated by
box **450** in Figure 3 and the construction of the
propagation model indicated by box **460** in the same
figure. Application of the propagation model to the
model input signal produces a model return signal.
The model return signal is usually expressed in the
frequency domain and may then be transformed to the
time domain (yielding a return pulse time domain
waveform) for purposes of comparison with actual
observed data.

The adjustment of the propagation model so as to
better replicate actual observed data is carried out
by means of a correlation step, as indicated by box
470 in Figure 3. The correlation step can be
implemented by any suitable measure, such as that
which will be described.

$E_1(t)$, the observed data, and $E_2(t)$, the
predicted data, are compared as follows:

$$H = \frac{[\Sigma_{n=1}^{N}[E_1(t_n) - E_{1M}] \quad [E_2(t_n)-E_{2M}]}{\sqrt{[\Sigma_{n=1}^{N}[E_1(t_n) - E_{1M}]^2 \cdot [\Sigma_{n=1}^{N}[E_2(t_n) - E_{2M}]^2}} \times 100 \quad (50)$$

where, $E_{1M} = (1/N)\Sigma_{n=1}^{N} E_1(t_n)$ and $E_{2M} = (1/N)\Sigma_{n=1}^{N} E_2(t_n)$.
Thus for N discrete values of time over the processed

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pulse waveform, H is calculated as a value ($-100 < H < +100$) that is sought to be maximized by the iterative process described by boxes **460**, **470**, **480**, and **490** of Figure 3. Note that equation (50) is a form of a linear correlation factor. Other correlation methods may also be utilized.

The parameter adjustment in step **480** of Figure 3 is based on perturbations of the conductivity, the dielectric property and the layer thickness together with the layer density, i.e., the number of horizons, N. The perturbations of the physical and electrical parameters can be carried out by any of several means. A preferred technique used by the inventor of the present invention is to alter the parameter values by a fixed percentage, and then increase or decrease that percentage (and the direction of the parameter change, i.e., increase in value or decrease) based on the outcome of subsequent correlation results, i.e., the value of H in equation (50).

The iterative process depicted in Figure 3 continues until the desired degree of correlation between the actual data and the response pulse predicted by the propagation model is obtained. This usually corresponds to a correlation of between 75% and 99%, i.e., a value of H between 75 and 99. At that point the iterative loop is terminated as shown in box **500** of Figure 3. The physical and electrical parameters of the propagation model which produced the desired degree of correlation describe the geoelectric column for that section of the earth's interior, as indicated by box **510** of Figure 3.

As previously mentioned, the basic electrical parameters of conductivity, dielectric and resistivity are subject to a frequency dependence in the frequency window used in the method of the

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present invention. For example, the conductivity in
the frequency window is related to the zero frequency
conductivity by the quantity:

$$\Delta \sigma_k = \sigma_k(f_{ref}) - \sigma_{Ks} \qquad (51)$$

5   The reference frequency conductivity in the frequency
window is differenced from the zero frequency
conductivity to determine the amount of conductivity
subject to frequency dependence. The zero frequency
conductivity can be determined in various ways,
10   according to methods known in the art. The reference
frequency best adapted to the purposes of the present
invention is 1 MHz. As an example, quoted values for
the zero frequency conductivity of sandstone are
(1/322) that of the total conductivity. The loss
15   tangent, Lt, is calculated as follows:

$$Lt_k = \frac{\sigma_k}{\epsilon_k \epsilon_0 \omega} \qquad (52)$$

The complex resistivity then becomes:

20   $$\rho_k = \rho_k^{re} - i\rho_k^{im} \qquad (53)$$

where the real, re, and the imaginary, im, parts are:

$$\rho_k^{re} = \frac{Lt_k}{\epsilon_k \epsilon_0 \; \omega \; (1+Lt_k^2)} \qquad (54)$$

25   $$\rho_k^{im} = \frac{\rho_k^{re}}{Lt_k} \qquad (55)$$

Now let:

30   $$F_s = \frac{(\omega\tau)^\alpha \; \sin \; \frac{(\alpha\pi)}{2} \; \epsilon_0\omega}{[1 + 2(\omega\tau)^\alpha \cos(\alpha\pi) + (\omega\tau)^{2\alpha}]} \qquad (56)$$

30

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and:

$$F_c = \frac{1+(\omega\tau)^\alpha \cos \frac{(\alpha\pi)}{2}}{[1 + 2(\omega\tau)^\alpha \cos\frac{(\alpha\pi)}{2} + (\omega\tau)^{2\alpha}]} \qquad (57)$$

whereupon:

$$\epsilon_{ks} = \epsilon_k + \Delta\sigma_k \frac{(1-F_c)}{F_s} \qquad (58)$$

and:

$$\epsilon_{k\infty} = \epsilon_k - \frac{(F_c)}{F_s} \Delta\sigma_k \qquad (59)$$

if equations (58 and 59) are calculated at the reference frequency. At all other frequencies in the spectrum the following electrical parameters can be calculated:

$$\sigma_k = \sigma_{ks} + \frac{(\epsilon_{ks}-\epsilon_{k\infty})(\omega\tau)^\alpha \sin\frac{(\alpha\pi)}{2} \epsilon_0\omega}{[1 + 2(\omega\tau)^\alpha \cos\frac{(\alpha\pi)}{2} + (\omega\tau)^{2\alpha}]} \qquad (60)$$

$$\epsilon_k = \epsilon_{k\infty} + \frac{(\epsilon_{ks}-\epsilon_{k\infty})[1+(\omega\tau)^\alpha \cos\frac{(\alpha\pi)}{2}]}{[1 + 2(\omega\tau)^\alpha \cos\frac{(\alpha\pi)}{2} + (\omega\tau)^{2\alpha}]} \qquad (61)$$

In these formulas, $\alpha = \alpha_k$ and $\tau = \tau_k$ for each stratum, which is designated by the index k.

In summary, the following physical and electrical parameters are subject to adjustment for

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each stratum, k, in the filter parameter adjustment
loop **490** of Figure 3:

$$\sigma_k, \quad \epsilon_k, \quad z_k, \quad \alpha_k, \quad \tau_k, \quad \sigma_{ks}.$$

The complex resistivity,

5

$$\rho_k^{re} - i\rho_k^{im},$$

is determined by equations (52), (53), (54), and
(55), which gives the profile of each parameter as a
function of depth, D. The frequency dependence is
given by equations (56), (57), (58), and (59).

10   Finally, the physical size and location of each of
these electrical entities is given by:

$$z_k = z_1, \quad z_2, \quad z_3 \quad . \quad . \quad . \quad .$$

The relation between depth, D and time along the
observed or the predicted waveform is given by

15   equations (39), (40), and (41).

As discussed previously, the propagation or
earth electrical model can be excited with a model
input pulse, as indicated by the inner integral of
equation (5). If, for example, $F_s(\tau)$ is defined to be

20   an impulse function, then:

$$\int_0^\infty \exp(-i\omega\tau) F_s(\tau) d\tau = \int_0^\infty \exp(-i\omega\tau) \delta(\tau) d\tau = 1 \quad (62)$$

The inventor of the present invention has found that
better results can be obtained if a more realistic
pulse, such as a square wave, is used:

25

$$\int_0^\infty \exp(-i\omega\tau) F_s(\tau) d\tau = \int_0^\infty \exp(-i\omega\tau) u(\tau) d\tau \quad (63)$$

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where, $u(\tau) = 1$ $(T_1 < \tau < T_2)$; else $u(\tau) = 0$. In
addition, the value of $T_2 - T_1$ may be set to a desired
amount, for example 5ns. Further waveform adjustment
can be made with a filter such as:

5

$$f_r(\omega) = \frac{-i\ A_n\omega}{A_0 - \omega^2 - iA_n\omega} \tag{64}$$

where for example $A_n = 2.08(10)^7$ and $A_o = 2.5(10)^{13}$.

10 The preceding discussion of the method of the
present invention has focused on obtaining the
physical and electrical parameters corresponding to
one layer or set of layers beneath the earth's
surface. After these parameters have been determined
to the desired degree of precision (based on the
15 degree of correlation between the actual data and the
modeled data), the iterative process is performed
again with actual data obtained from a new time
window. Since the new time window corresponds to a
different depth regime in the earth, a progression of
20 data from different time windows can be used to
validate the results of the model for multiple
layers, eventually producing a complete geoelectric
column model for a location.

In accordance with the present invention, there
25 is presented a method for determining the physical
and electrical parameters corresponding to the
subsurface regions beneath a location on the earth's
surface. An earth capacitor apparatus is used to
inject a pulse into the earth's surface. The pulse
30 propagates into the earth, resulting in a return
pulse which is detected and stored. The actual
return pulse data is then used to validate parameters
selected for a propagation model of the subsurface
regions.

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The propagation model treats the earth's interior as a set of vertically stacked horizontal layers, each characterized by a depth, thickness, complex conductivity (or resistivity), and relative dielectric constant. A model input pulse is used to represent the injected pulse, and the propagation model is applied to the model pulse to produce simulated return pulse data. Comparison between the actual return pulse data from a specific time window (and hence an approximate depth regime) and the simulated return pulse data is used as the basis for adjusting the parameters of the propagation model.

The process is continued in an iterative fashion until a desired degree of correlation is obtained between the actual data and the simulated data. The process can then be extended to additional layers and/or locations until a model of the physical and electrical properties of the subsurface layers is established. This model can be used to assist with determining the type and character of subsurface geologic formations, thereby assisting with geophysical exploration.

The terms and expressions which have been employed herein are used as terms of description and not of limitation, and there is no intention in the use of such terms and expressions of excluding equivalents of the features shown and described, or portions thereof, it being recognized that various

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modifications are possible within the scope of the invention claimed.

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I claim:

1.   A method for processing a return
electromagnetic pulse that has propagated through a
subterranean formation from a capacitor, including
5   the steps of:

(a) selecting an initial geoelectric column
model which determines a set of filter coefficients
indicative of one or more electromagnetic properties
of a set of vertically stacked horizontal layers of
10   the subterranean formation;

(b) generating a simulated return pulse by
applying the filter coefficients to a model input
electromagnetic pulse, where the simulated return
pulse represents response of the formation to
15   application of the model input electromagnetic pulse;
and

(c) generating a modified geoelectric
column model which results in increased correlation
between the return electromagnetic pulse and a
20   simulated return pulse predicted by the modified
geoelectric column model, relative to correlation
between the return electromagnetic pulse and a
simulated return pulse predicted by the initial
geoelectric column model.

25   2.   A method for processing a return
electromagnetic pulse that has propagated through a
subterranean formation from a capacitor, including
the steps of:

(a) selecting a geoelectric column model,
30   said model determining a set of filter coefficients
indicative of properties of vertically stacked
horizontal layers of the subterranean formation;

(b) generating a simulated return pulse by
applying the filter coefficients to a model input
35   electromagnetic pulse, where the simulated return

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pulse represents a response of the formation,
measured at a first location of the formation during
a first time window after application of the model
input electromagnetic pulse to the first location;

5   (c) correlating a detected portion of the
return electromagnetic pulse with the simulated
return pulse, wherein said detected portion of the
return electromagnetic pulse is detected during the
first time window after application of an input
10 electromagnetic pulse to the formation;

              (d) generating a modified geoelectric
column model defined by modified filter coefficients
selected for increasing correlation during a
subsequent repetition of step (c); and

15   (e) repeating steps (b) through (d) using
the modified filter coefficients in place of the
filter coefficients, until a desired degree of
correlation is achieved in the final repetition of
step (c).

20   3.   The method of claim 2, also including the
step of:

              (f) applying the input electromagnetic
pulse to the subterranean formation from a capacitor
at said first location.

25   4.   The method of claim 3, wherein step (f)
includes the steps of:

              disposing capacitor plates having a largest
dimension L in direct contact with the formation at
said first location, to form an earth capacitor
30 comprising the plates and a region of the formation
near the plates; and

              applying a short voltage pulse across the
capacitor plates to transmit the input
electromagnetic pulse into the formation, wherein for

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each frequency component of the input electromagnetic pulse, the largest dimension L satisfies the relation Re[kL] < 1, where k is the wavenumber in the formation of said frequency component, and further, wherein the short voltage pulse has frequency components in a broad band extending from below 1 MHz to above 100 MHz.

5. The method of claim 4, also including the steps of:

detecting a return portion of the input electromagnetic pulse after said input electromagnetic pulse has propagated through the formation in response to application of the short voltage pulse, and wherein said portion of the return electromagnetic pulse processed in step (c) includes only frequency components of the detected return portion in a frequency window having an upper frequency less than 25 MHz.

6. The method of claim 2, also including the steps of:

(g) after step (e), selecting an expanded geoelectric column model comprising an expanded set of filter coefficients, said expanded set including the modified filter coefficients generated during the final repetition of step (d), and additional filter coefficients indicative of an additional layer of the subterranean formation;

(h) after step (g) repeating steps (b) through (e) using the expanded set of filter coefficients to generate a modified, expanded geoelectric column model.

7. The method of claim 2, also including the steps of:

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(g) after step (e), repeating steps (b) through (e), with the simulated return pulse representing a response of the formation measured at the first location during a second time window after application of the model input electromagnetic pulse to the first location, and with the detected portion of the return electromagnetic pulse detected during the second time window after application of the input electromagnetic pulse to the formation.

8. The method of claim 2, wherein step (d) includes the step of applying a spectrum normalizing filter to the modified filter coefficients, and wherein step (c) includes the step of applying a spectrum normalizing filter to the detected portion of the return electromagnetic pulse before correlating said detected portion of the return electromagnetic pulse with the simulated return pulse.

9. The method of claim 2, also including the step of:
determining a resistivity model from the modified geoelectric column model determined during the final repetition of step (d), said resistivity model determining a resistivity of each of the vertically stacked horizontal layers.

10. The method of claim 2, also including the step of:
determining a dielectric coefficient model from the modified geoelectric column model determined during the final repetition of step (d), said dielectric coefficient model determining a dielectric coefficient of each of the vertically stacked horizontal layers.

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11.   The method of claim 2, also including the step of:

determining an electrical property of each of said vertically stacked horizontal layers as a function of frequency, from the modified geoelectric column model determined during the final repetition of step (d).

12.   A method for determining electromagnetic properties of a subterranean formation, including the steps of:

(a) transmitting an electromagnetic pulse into the formation by disposing capacitor plates having a largest dimension L, in direct contact with the earth formation to form an earth capacitor comprising the plates and a region of the earth formation near the plates, and applying a short voltage pulse across the capacitor plates to transmit electromagnetic radiation into the earth formation, wherein for each frequency component of the electromagnetic radiation, the largest dimension L satisfies the relation Re[kL] < 1, where k is the wavenumber in the earth formation of said frequency component, and further, wherein the short voltage pulse has frequency components in a broad band extending from below 1 MHz to above 100 MHz;

(b) detecting a return electromagnetic pulse that has propagated through the earth formation in response to application of the short voltage pulse; and

(c) processing only frequency components of the return electromagnetic pulse, in a frequency window having an upper frequency less than 25 MHz, which have propagated into the earth formation to a penetration depth much greater than on the order of
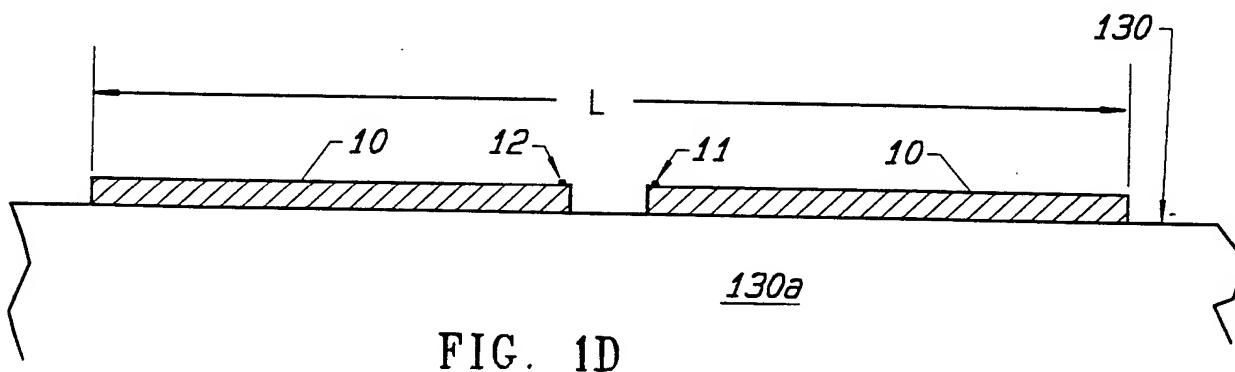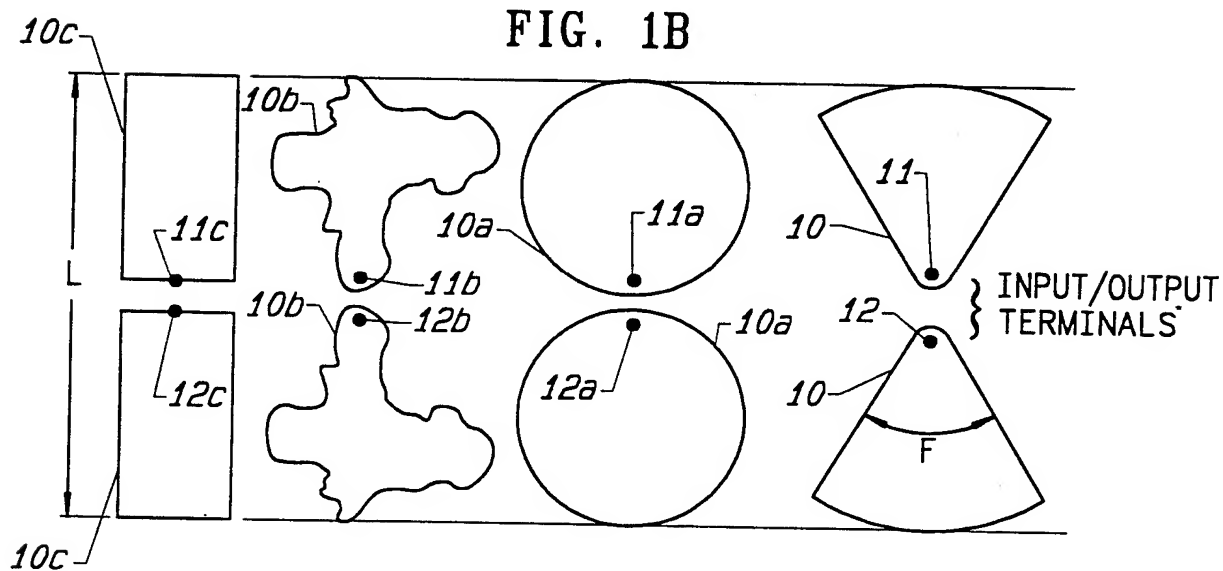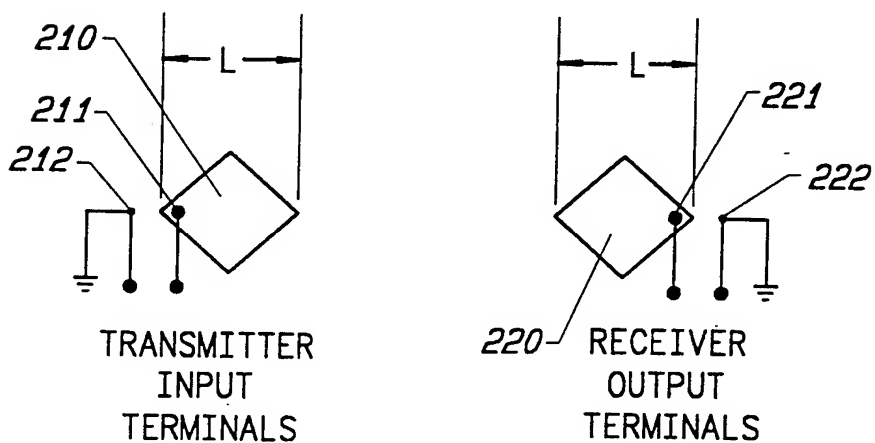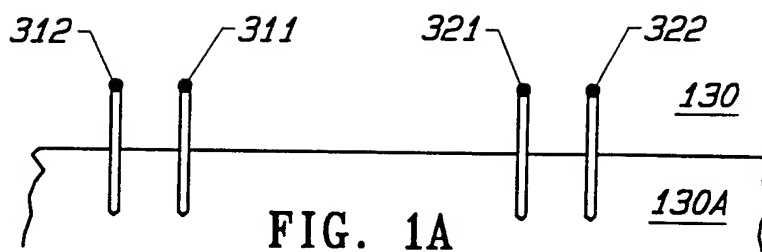
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several hundred feet, to determine a geoelectric
column model which determines one or more
electromagnetic properties of a set of vertical
layers of the formation.

5   13.   The method of claim 12, wherein step (c)
includes the steps of:
       selecting an initial geoelectric column
model which determines a set of filter coefficients
indicative of one or more electromagnetic properties
10   of a set of vertically stacked horizontal layers of
the formation;
       generating a simulated return pulse by
applying the filter coefficients to a model input
electromagnetic pulse, where the simulated return
15   pulse represents response of the formation to
application of the model input electromagnetic pulse;
and
       generating a modified geoelectric column
model which results in increased correlation between
20   said frequency components of the return
electromagnetic pulse and a simulated return pulse
predicted by the modified geoelectric column model,
relative to correlation between said frequency
components of the return electromagnetic pulse and a
25   simulated return pulse predicted by the initial
geoelectric column model, and identifying said
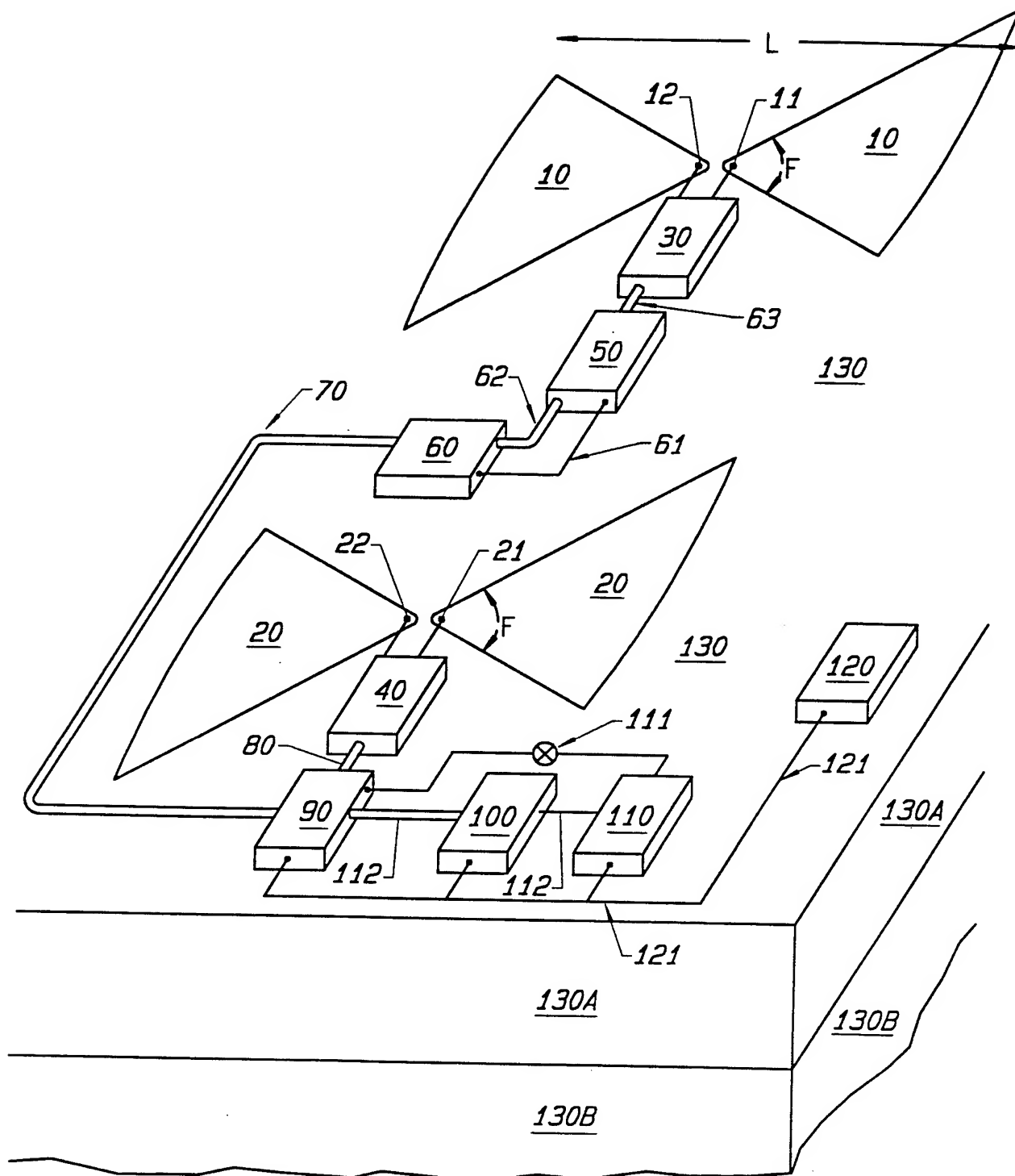modified geoelectric column model as said geoelectric
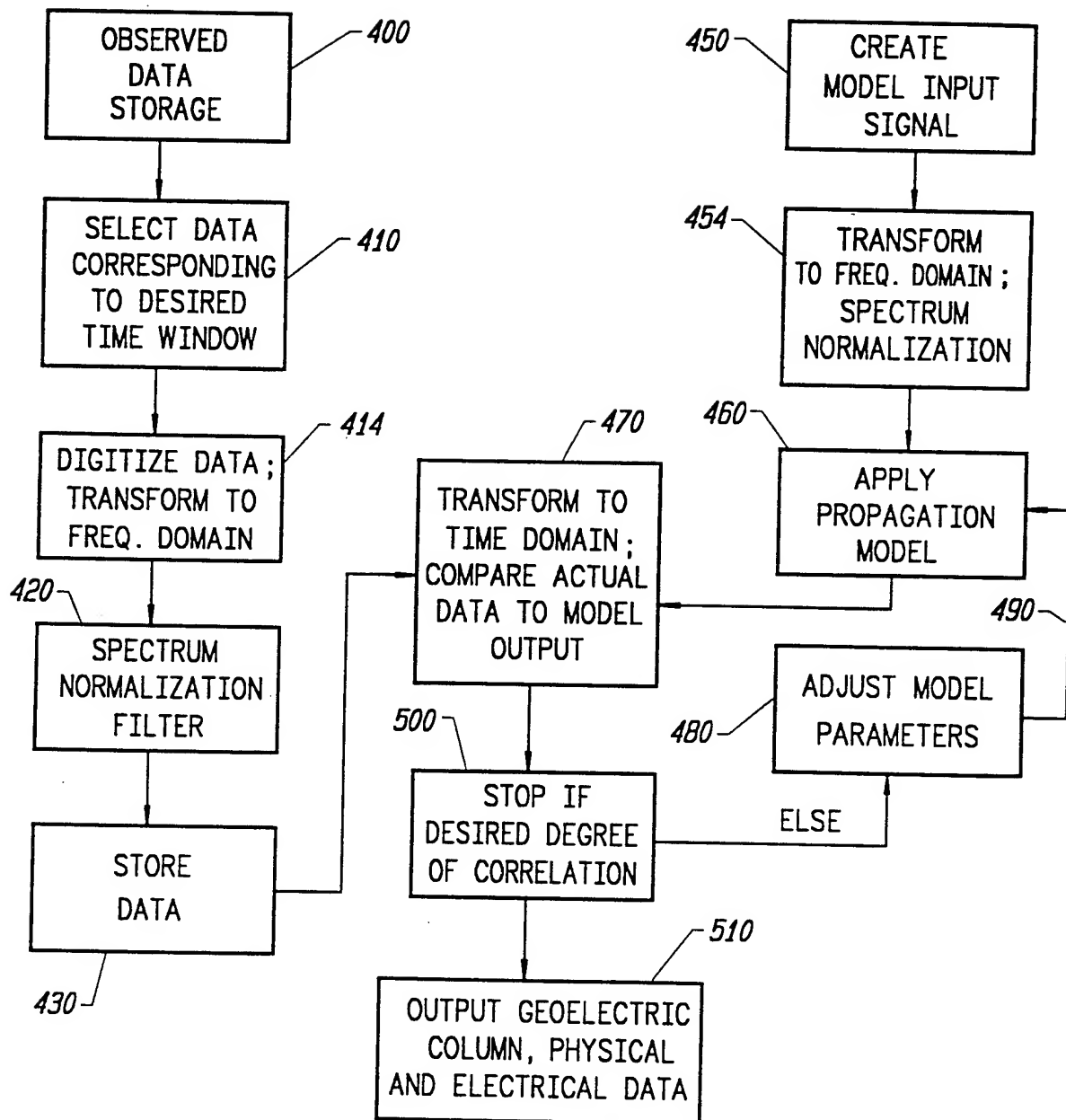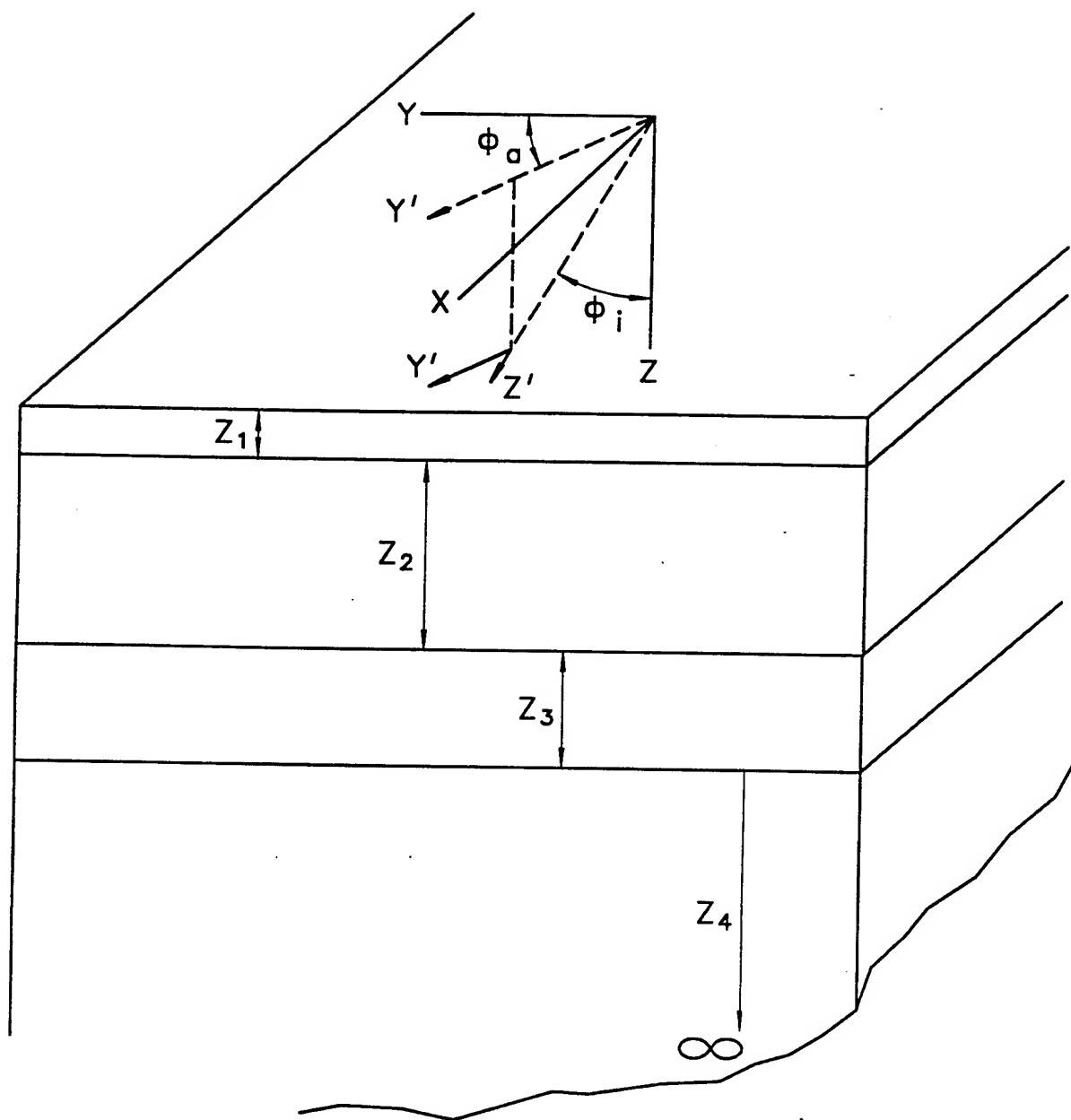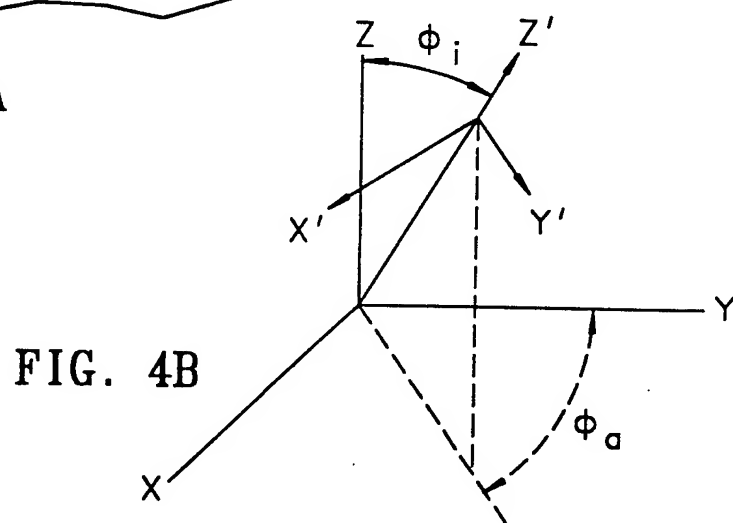column model.

FIG. 1A

TRANSMITTER
INPUT
TERMINALS

RECEIVER
OUTPUT
TERMINALS

FIG. 1B

INPUT/OUTPUT
TERMINALS

FIG. 1C

FIG. 1D

FIG. 2

FIG. 3

FIG. 4A

FIG. 4B

INTERNATIONAL SEARCH REPORT

A. **CLASSIFICATION OF SUBJECT MATTER**	

IPC(5)   :GO1S 13/04
US CL   :342/22, 189, 196, 191

According to International Patent Classification (IPC) or to both national classification and IPC

B.   **FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)

  U.S. :   342/22,189,196,191
342/27,195,190,192; 324/323,326,327,328,332

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C.   **DOCUMENTS CONSIDERED TO BE RELEVANT**

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A, P	US, A, 5,280,284 (JOHLER) 18 January 1994.	1-13.
A	US, A, 5,113,192 (THOMAS) 12 May 1992.	1-13.
A	US, A, 5,057,844 (ROTHSTEIN) 15 October 1991.	1-13.
A	US, A, 2,077,707 (MELTON) 20 April 1937.	1-13.
A	US, A, 5,051,748 (PICHOT ET AL) 24 September 1991.	1-13.
A	US, A, 4,937,580 (WILLS) 26 June 1990.	1-13.
A	US, A, 4,905,008 (KAWANO ET AL) 27 February 1990.	1-13.
A	US, A, 4,837,514 (SPIES) 06 June 1989.	1-13.

[X] Further documents are listed in the continuation of Box C.   [ ] See patent family annex.

*	Special categories of cited documents:	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be part of particular relevance		
"E"	earlier document published on or after the international filing date	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)		
		"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"O"	document referring to an oral disclosure, use, exhibition or other means		
"P"	document published prior to the international filing date but later than the priority date claimed	"&"	document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
20 MAY 1994	JUN 09 1994

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C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US, A, 4,746,867 (GUNTON) 24 May 1988.	1-13.
A	US, A, 4,651,152 (HARMUTH) 17 March 1987.	1-13.
A	US, A, 4,417,210 (ROCROI ET AL) 22 November 1983.	1-13.
A	US, A, 4,245,191 (SCHROEDER) 13 January 1981.	1-13.
A	US, A, 4,126,860 (SULLIVAN ET AL) 21 November 1978.	1-13.
A	US, A, 4,062,010 (YOUNG ET AL) 06 December 1977.	1-13.
A	US, A, 4,008,469 (CHAPMAN) 15 February 1977.	1-13.
A	US, A, 3,831,173 (LERNER) 20 August 1974.	1-13.
A	US, A, 3,806,795 (MOREY) 23 April 1974.	1-13.
A	US, A, 2,517,951 (WHEELER) 08 August 1950.	1-13.
A	US, A, 1,365,579 (APPLEBY ET AL) 11 January 1921.	1-13.